RUN II BEAUTY PHYSICS AT CDF AND DØ

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The Tevatron begins Run II on March 1, 2001, generating $\overline{p}p$ interactions at a collision energy of $\sqrt{s} = 1.96$ TeV. With an instantaneous luminosity of 2×10^{32} cm^{-2}s^{-1}, the Tevatron promises to deliver 2 fb^{-1} to the CDF and DØ detectors in the first two years of running. Both detectors have been upgraded to take full advantage of the higher luminosity conditions. Now the CDF and DØ collaborations are preparing to perform several B physics studies in Run II. We describe several of the studies aimed towards constraining the CKM matrix and understanding CP violation, namely, the unitarity angles α, β and γ, and the B_s mixing parameters.

1 Introduction

In the era of e^+e^- B factories, the Tevatron $\overline{p}p$ collider remains a practical and complementary tool for studying the b quark. Beauty hadrons are copiously produced at the Tevatron, where the $\overline{p}p \to \overline{b}b$ interaction cross section (see Fig. 1 [1]) is predicted to be 150 μbarns at the Run II collision energy of $\sqrt{s} = 2$ TeV. Compared to the $e^+e^- \to \overline{B}B$ interaction cross section of 1 nanobarn at the $\Upsilon(4S)$, this represents a large rate of b quark production. On the other hand, the backgrounds at the $\overline{p}p$ collider are substantially larger than at e^+e^- machines. Furthermore, contrary to the case at e^+e^- machines, the $\overline{b}b$ partners are only correlated at production, thereafter hadronizing completely independently into their respective final states. Finally, another advantage the Tevatron has over the e^+e^- B factories is that all species of b hadrons, including the B_d, B_u, B_s and B_c mesons and the Λ_b baryon, are produced and can be studied at the Tevatron.

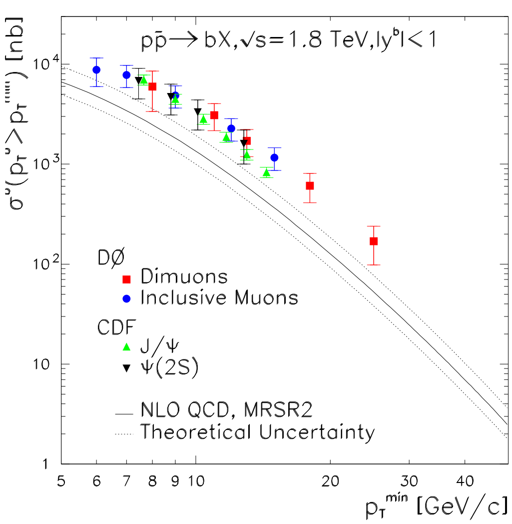

Figure 1: Interaction cross section for $p\overline{p} \to b\overline{b}$ at the Tevatron [1].

The CDF and DØ collaborations are preparing to perform several B physics studies in Run II. These include, but are not limited to, studies associated with CP violation and the extraction of the CKM angles β, α and γ, B_s mixing and numerous spectroscopy, lifetime, rare decay and cross section measurements. As shown in Fig. 2[2], it is possible to constrain the angles of the unitarity triangle at the Tevatron by performing measurements of B_s mixing and $\sin(2\beta)$.

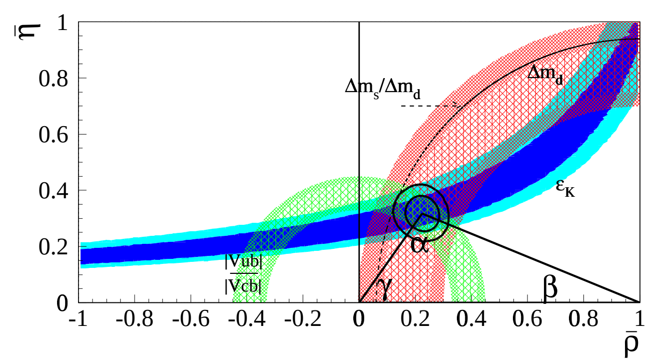

Figure 2: Existing constraints on the unitarity triangle [2].

2 Run II Detectors

Both the CDF and DØ detectors have undergone major upgrades to take full advantage of the Tevatron Run II environment. In addition to the excellent Run I calorimeter [3], DØ now has a 2 Tesla solenoidal magnet, a scintillating fiber tracker [4] and a silicon microstrip vertex detector [5] for improved tracking. Preshower detectors [6] enhance electromagnetic shower identification capabilities in the central and forward regions. The extensive muon system has been upgraded to improve the spatial resolution and allows reduced trigger thresholds. The new DØ trigger system includes a central track trigger at Level 1. In addition, one year into Run II, a Level 2 impact parameter trigger [7] will be installed.

The upgraded CDF detector has a five-layer silicon vertex detector [8], layer 00 silicon installed on the beam pipe, and intermediate silicon layers [9] inside the new central outer tracker [10]. A time-of-flight [11] detector and a new EM plug calorimeter improve the particle identification capabilities. The new CDF trigger system includes a pipe-lined central track trigger at Level 1 [12] and a Level 2 impact parameter trigger [13]. These improvements make a two-track hadronic trigger possible at Level 2.

3 CP Violation

One of the most interesting properties of the neutral B mesons is mixing, where the particle spontaneously changes into its antiparticle. In the B system, the direct and mixed decays yield the same CP eigenstate at different rates. This CP asymmetry can be measured and is directly related to the angle β of the unitarity triangle.

At the Tevatron, the time-dependent CP asymmetry, A_{CP}, is measured using $B^0 \to J/\psi K_s^0$ decays, where

$$A_{CP}(t) = \frac{\Gamma(\overline{B}^0 \to J/\psi K_s^0) - \Gamma(B^0 \to J/\psi K_s^0)}{\Gamma(\overline{B}^0 \to J/\psi K_s^0) + \Gamma(B^0 \to J/\psi K_s^0)}, \quad (1)$$

$$= \sin(2\beta)\sin(\Delta m_d t)\,. \quad (2)$$

The $J/\psi \to \ell^+\ell^-$ signature is used for the trigger and the $K_s^0 \to \pi^+\pi^-$ decay is reconstructed by looking for opposite-sign tracks in the vicinity of the J/ψ candidate. Mass constraints on the J/ψ and K_s^0 candidates are imposed simultaneously with the vertex and pointing constraints.

The charge correlation between the “same-side” b quark and a nearby pion from fragmentation or B^{**} decay can sometimes be exploited to determine the flavour of the B^0 meson at the time of production. In other cases, the production flavour is determined from the flavour of the other b quark produced in the $\overline{p}p$ interaction. This “opposite-side tag” is obtained from the charge of the lepton from the b-quark semileptonic decay, or from the p_T-weighted net charge of the particles in the b jet.

The quality of the flavour tag is given by $\varepsilon\mathcal{D}^2$, where ε is the tagging efficiency and $\mathcal{D} = 2\mathcal{P} - 1$ is the dilution, related to the probability $\mathcal{P}$ that a tag gives the correct flavour. In Run I, CDF calibrated the tagging efficiencies using $B^\pm \to J/\psi K^\pm$ decays [15], where the charge of the kaon defines the flavour. These results were extrapolated by both experiments to reflect the conditions expected in Run II. Table 1 shows the predicted tagging efficiencies for both CDF and DØ.

Using 110 pb^{-1} of $\overline{p}p$ collisions collected in Run I, CDF determined the result $\sin(2\beta) = 0.79^{+0.41}_{-0.44}(stat + syst)$ [15] (see Fig. 3).

Table 1: Predicted tagging qualities for CDF and DØ in Run II.

Tag	$\varepsilon\mathcal{D}^2$ (%) Run I measured CDF	Run II expected CDF	Run II expected DØ
Same side	$1.8 \pm 0.4 \pm 0.3$	2.0	2.0
Soft lepton	$0.9 \pm 0.1 \pm 0.1$	1.7	3.1
Jet charge	$0.8 \pm 0.1 \pm 0.1$	3.0	4.7
Opp. side K		2.4	none
Combined		9.1	9.8

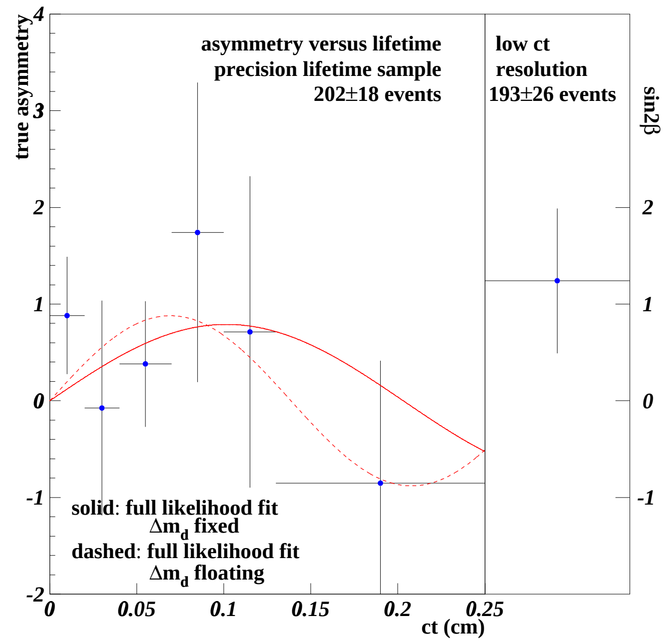

Figure 3: A_{CP} versus decay length for $B^0 \to J/\psi K_s^0$ events measured by CDF in Run I [15].

The resolution on the measurement of $\sin(2\beta)$ is given by

$$\sigma(\sin(2\beta)) \approx e^{x_d^2\Gamma^2\sigma_t^2}\sqrt{\frac{1+4x_d^2}{2x_d}}\frac{1}{\varepsilon D^2 N}\sqrt{1+\frac{B}{S}}. \quad (3)$$

Here, Γ and $x_d = \Delta m_d/\Gamma$ are the decay width and mixing parameter, respectively, of the B^0 meson, σ_t is the proper time measurement resolution (expected to be about 90 fs), N is the number of events and S/B is the signal to background ratio (which is expected to be about 0.75 at DØ for example). With 2 fb^{-1} of integrated luminosity, CDF expects to reconstruct 30 000 decays in the $J/\psi \to \mu^+\mu^-$ channel and 12 000 decays in the $J/\psi \to e^+e^-$ channel. DØ expects 40 000 decays in the $J/\psi \to \mu^+\mu^-$ channel and 30 000 decays in the $J/\psi \to e^+e^-$ channel. These expectations yield a prediction for the final resolution on $\sin(2\beta)$ of 0.04, to be measured by CDF using 2 fb^{-1} of $\overline{p}p$ collisions and $\sigma(\sin(2\beta))$ of 0.03, to be measured by DØ, with the same integrated luminosity. This improved resolution is a result of the increased muon acceptance and lower muon trigger thresholds, improved flavour tagging and forward tracking, in the case of DØ. This result continues to be statistics limited due to the size of the tagging calibration samples.

4 α and γ in $B_{(s)}$ Decays

When the decay $B^0 \to \pi^+\pi^-$ was thought to be dominated by tree-level diagrams, it was the prime candidate for measuring $\sin(2\alpha)$ from its CP asymmetry. Despite the low branching fraction of order 10^{-5} and large backgrounds (mostly heavy flavour daughters), CDF expects to reconstruct 5000 such events, using its all-hadronic trigger. DØ has no such capability, but can trigger on the opposite-side lepton, thereby collecting 500 events in 2 fb^{-1}. Unfortunately, it is now clear that this decay is complicated by penguin contributions, making the A_{CP} difficult to extract from this mode alone.

Using the prescription described in Ref. 12, the angles, α and γ, of the unitarity triangle can be determined in a single measurement. The four decays, $B^0 \to \pi^+\pi^-$, $B^0 \to K^+\pi^-$, $B_s^0 \to \pi^+K^-$, and $B_s^0 \to K^+K^-$ are reconstructed simultaneously. The decays are expected to be produced in the ratios 1:4:0.5:2. Without significant K/π separation capability at DØ, only fits to the masses and decay times can be used to separate these decays from each other. To illustrate this point, Fig. 4 shows the predicted invariant mass distributions at DØ for $B_{(s)}$ candidates from these four decay channels, where the pion mass is assigned to both daughter tracks. On the other hand, although the CDF Time-of-Flight detector only provides substantial K/π separation for momenta up to $p = 1.6$ GeV/c, too low for the daughter tracks of these two-body decays, the CDF dE/dx information does allow a 1-σ K/π separation in this regime. This helps to distinguish the $B^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$ decays, which otherwise have the least invariant mass separation of the four channels.

Although the mass distributions cannot be easily distinguished, these decay channels have different oscillation frequencies. Therefore, a likelihood fit can be performed to the observed A_{CP} distribution. Five observables appear in the fit: $A_{CP}^{dir}(\pi^+\pi^-)$, $A_{CP}^{dir}(K^+K^-)$, $A_{CP}^{mix}(\pi^+\pi^-)$, $A_{CP}^{mix}(K^+K^-)$, and $\sin(2\beta)$. CDF predicts a measurement of γ with resolution $\sigma(\gamma) =^{+5.4}_{-6.8} \pm 3$ degrees. The resolution of such a measurement at DØ is still under study.

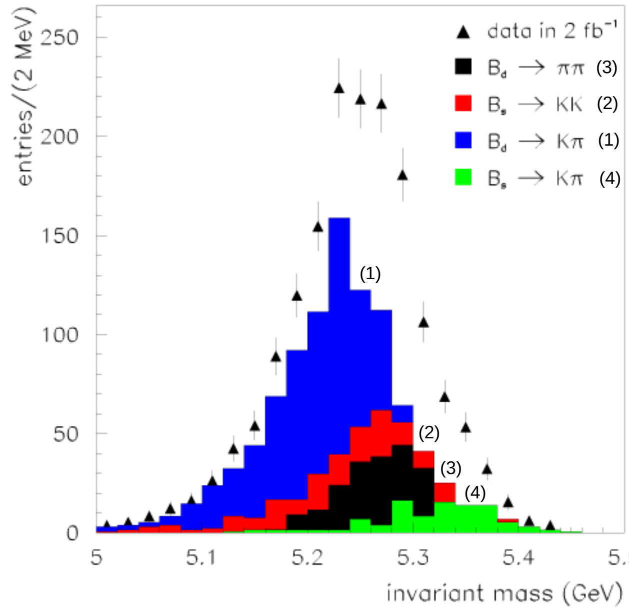

Figure 4: Expected $\pi\pi$ invariant mass distribution for B^0 and B_s^0 candidates in 2 fb^{-1} at DØ where the pion mass has been assigned to the two daughter tracks. The shaded areas each represent a decay channel. The points represent the sum of all channels.

5 B_s Mixing

The unitarity triangle can also be constrained by studies of B_s^0 mixing, physics not accessible to the e^+e^- B factories running at the $\Upsilon(4S)$. With 2 fb^{-1} of $\overline{p}p$ collisions, both CDF and DØ expect to reconstruct about 40 000 B_s^0 semileptonic decays, which can be used to probe values of the mixing parameter Δm_s up to about 20 ps^{-1}. CDF performed such a study in Run I with 110 pb^{-1} of $\overline{p}p$ collisions and measured $\Delta m_s > 5.8$ ps^{-1} at 95% confidence level[16] (see Fig. 5).

If the value of Δm_s turns out to be large, the resolution in the semileptonic mode will be insufficient, due to the momentum uncertainty of the missing neutrino. However, larger values of Δm_s can be studied in the $B_s^0 \to D_s^-\pi^+(\pi^-\pi^+)$ decay channel. The D_s meson is reconstructed in the $\phi\pi$ decay mode, where $\phi \to K^+K^-$. CDF uses the two-track hadronic trigger and tags the initial flavour by the opposite-side event. In addition to the tags used in the $B^0 \to J/\psi K_s^0$ reconstruction, CDF can also use the charge-correlation of the opposite-side fragmentation kaon, a direct benefit of CDF's particle-ID capability. The final flavour is tagged by the charge of the D_s meson. CDF expects to reconstruct between 5000 and 30 000 decays in 2 fb^{-1} and can probe values up to $\Delta m_s = 40$ ps^{-1}. In the absence of a fully-hadronic trigger, DØ triggers on the opposite-side lepton and uses the lepton charge to tag the initial flavour. Between 400 and 1200 reconstucted events are expected at DØ and

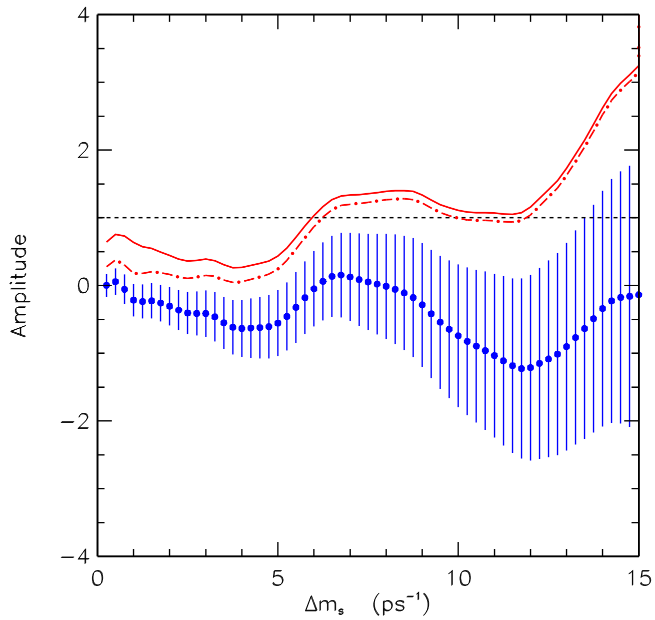

Figure 5: The B_s^0 oscillation amplitude as a function of Δm_s measured by CDF in Run I. The points represent the data. The lines represent the predictions at 95% CL, where the solid line includes statistical and systematic uncertainties and the dot-dashed line includes statistical uncertainties only[16].

values up to $\Delta m_s = 22$ ps^{-1} can be studied.

6 Tevatron Run II Schedule

The Tevatron Run II begins on March 1, 2001. The Fermilab directorate has promised no long shutdowns throughout the duration of the run. The beams division expects a gradual luminosity improvement over time, reaching the design luminosity of 2.0×10^{32} cm^{-2}s^{-1} by 2004. The Tevatron will start with a 396 ns bunch spacing, reduced to 132 ns in 2003. Both CDF and DØ hope to accumulate 15 fb^{-1} of $\overline{p}p$ collisions by 2008, at which point the BTeV experiment will become the focus of the Tevatron program.

7 Conclusion

The prospects for successful B physics studies in Run II at the Tevatron are excellent. With competitive measurements of quantities such as $\sin(2\beta)$, γ and Δm_s, the CDF and DØ experiments will continue to make valuable contributions to the B physics program with the large data samples available in the just the first two years of Run II at the Tevatron.

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